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Group Art Unit

1746Invention: **POTTED TRANSDUCER ARRAY WITH MATCHING NETWORK IN A MULTIPLE PASS CONFIGURATION**I hereby certify that this **Declaration (2 pages) with Attachment #1 (20 pages)**

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| Applicant: | Schuler, et. al |) | |
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| For: | POTTED TRANSDUCER |) | |
| | ARRAY WITH MATCHING |) | |
| | NETWORK IN A MULTIPLE |) | |
| | PASS CONFIGURATION |) | |
| | |) | |

DECLARATION UNDER 37 CFR §1.131

1. I/We am an inventor of the subject application.
2. On or before July 22, 1998, I/we conceived and reduced to practice the invention disclosed in the subject applicaiton.
3. Attached to this Declaration is a copy of a document authored by me/one of the co-inventors. Page 1 of Section 1 describes front to back motion of the wafer across the columns of megasonic waves.
4. I believe that portion of the document corresponds to the subject matter found in claims 13, 14 and 27.
5. The document describes the results of an improved megasonic cleaning apparatus.
6. The apparatus was made and tested before June 2, 1997.

7. All statements made herein of my own knowledge are true, all statements made herein on information and belief are believed to be true, and these statements were made with the knowledge that willful false statements and the like are punishable by fine or imprisonment, or both, under 18 U.S.C. 1001, and may jeopardize the validity of the application or any patent issuing thereon.

Robert F. Longenberger

Attachment #1

IMPROVEMENTS TO THE MEGASONIC CLEANING OF SILICON WAFERS

Robert F. Longenberger

Harris Semiconductor

Mountaintop, Pennsylvania 18707

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HARRIS
SEMICONDUCTOR

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PREFACE

This project has been conducted with a considerable amount of assistance from many coworkers. A special acknowledgment to the members of the Clean Team, Mike Caravaggio, Tom Grebbs, Rick McEntee, Malcolm Schuler, Frank Stensney, and Ray Webb, who were very instrumental in performing process analyses, presenting the challenges to the project, making suggestions, providing the innovative component designs, running the particle tests, developing the graphics, and overall support. A very special thanks to the Unique Solutions team who fabricated most of the components and the final assembly of the Clean Bench. A special thanks to Larry Weldon of Blatek Incorporated for assistance in the new transducer development, George White of Leighton Electronics for making the fabrication of the power generators possible, and also to Alfred Mayer, the father of Megasonic cleaning systems, for his guidance through his original work.

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ABSTRACT

The principle objective of this project was to improve the cleaning ability of the wet benches used in the fabrication of semiconductor devices and to reduce the number of defects caused by particulate contamination. The end result of this cleaning improvement is to enhance the yield of the finished products which will reduce the overall manufacturing cost of the devices.

After the initial cleaning ability of the wet benches was determined, a series of improvements were introduced. First a newly designed transducer was integrated and tested for performance. Pulsing the RF excitation gave a marked improvement to the cleaning ability without exceeding the average power delivered to the transducer. The original tank design was then examined and a suitable design had been fabricated with a considerably reduced footprint and with an ability to be adapted to robotic systems. Tantalum covered the face of the original transducer. The new design totally eliminated the presence of metal on the tank. Rinsing then had to be addressed. Previous tanks used a hot or cold overflow and some were quick dump rinse. Quick dump rinse was one of the most effective rinse techniques but still did little for particle removal. A "drop-in" Megasonic transducer assembly was designed to aid in the removal of particles. Cleaning had reached a new high but the excitation of the transducer was still an issue. The original RF source had severe limitations of power and frequency. Searches for a better amplifier proved fruitless due to reliability issues and a power generator had to be developed. A total class D (digital) generator with a phase locked loop frequency control was designed and built.

The new system design had several immediate paybacks. The cost of the new transducers was one fourth of the original ones and the newly designed power generators cost less than half of the initial model. Generator reliability issues became non existent. The new transducer has a nearly perfect impedance match to the generator so energy transfer is extremely efficient and the new generator uses less than half the power of the original system. Wafer particle removal in excess of 97% was now possible with an improvement in probe yield being immediately evident. Cleaning has reached world class with these developments.

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SECTION I

INTRODUCTION

The improvement of the cleaning of silicon wafers used in the manufacturing of semiconductors has been a continuing effort at the Harris Semiconductor facility located in Mountaintop, Pennsylvania, since the earliest days of its operation. The initial experiments for Megasonic cleaning in a manufacturing environment were conducted at the Mountaintop plant during the time when it was part of the RCA Solid State Division with the laboratory tests being run in the Somerville operations in the 1970s⁽¹⁾. The original work was conducted to provide a very clean substrate for the manufacturing of flat plate photovoltaic solar cell arrays. The results of the initial work by Mayer and Shwartzman were excellent and Megasonic cleaning became an integral part of the bulk of wafer fabrication at the Mountaintop plant. The systems used were manufactured by Fluorocarbon (now Vertec), a licensee of the original patent, and performed adequately but as experience was gained it was apparent that the basic system could be improved.

A series of experiments were conducted to eliminate the presence of the metals in the bath, particularly the tantalum foil surface of the original megasonic transducer, in addition to improving the cleaning efficiency of the wet bench in general. In doing these tests it was also determined that an alternative to the function generator/ power amplifier pair was needed. The results of this work done by the Mountaintop Clean Team has brought the Megasonic cleaning to a new level with some added benefits, specifically:

- (1) A smaller footprint of the SC1 (ammonium hydroxide and hydrogen peroxide, $\text{NH}_4\text{OH} + \text{H}_2\text{O}_2$) bath since the wafer carriers are moved front to back rather than left to right. This allows loading and unloading from a common point making the use of robotic control more feasible.
- (2) The motion of the carrier in a front to back to front transition gives an double pass over the transducers and a double cleaning for the same insertion.
- (3) Transducers have been redesigned with either a face of PVDF (polyvinylidene fluoride, Kynar® trademark of DuPont) or 5/4λ quartz. Elimination of metal contaminants in the bath is the result.
- (4) A recirculating filter system for the SC1 to remove the suspended particles from the bath was added. A reduction in the reattachment of particles onto the wafers is realized after the process is completed.
- (5) The use of analog function generators have inherent drift and poor accuracy, a phase locked loop generator on the other hand has the

accuracy of its reference crystal, +/- .005%. Replacement with the latter provided a great advantage.

- (6) Power efficiency in excess of 85% is achieved with the use of class D operation compared with efficiencies of approximately 30% in class C operation. High efficiencies are attained with the use of power MOS output devices and CMOS logic control.
- (7) The introduction of Megasonic transducers into the quick dump rinse tanks added a new level of cleaning to the bench.
- (8) Major cost avoidances are:
 - (a) The original design of the transducer incorporated a tantalum face in the bath chemistry and had a selling price of \$6000 from Veriteq. In addition the matching of the transducer impedance to the amplifier is somewhat poor. A newer custom designed transducer with either PVDF or quartz faces and a perfectly matched load characteristic were purchased for \$1500 each from Blatek, Incorporated of State College, Pennsylvania, a cost avoidance of \$4500 each with superb reliability.
 - (b) The original system employed a \$5000 ENI 1040L class C power amplifier and a \$500 Heath function generator. The 1040L had serious rolloff starting at 500KHz and was replaced with a \$6000 ENI 400B. The 400B had much better rolloff characteristics but had a high failure rate when operated in a pulsed mode. A newly designed \$2000 class D power generator capable of operation to 1.2 MHz at powers up to 1KW CW or pulsed was the answer. Cost avoidance of \$4500 per unit was achieved in addition to better operational efficiencies giving lower overall power consumption improvements of over 50%.

In the technical discussion the details of the experiments will be examined as will the factors that effected the choices in the finished design. These tests were conducted at the Harris Semiconductor Sector manufacturing plant located in Mountaintop, Pennsylvania. Although the tests have resulted in a finished design in the wafer cleaning bench, work on other aspects of the process improvement is continuing.



SECTION II

TECHNICAL DISCUSSION

A. SYSTEM DESIGN

1. Background

The system to remove particle contaminants from the surface of semiconductor wafers is key to improve the yield of the finished product. By employing this method of Megasonic cleaning, an immediate improvement of finished product yield can be had by reduction in the number of particle related defects across the wafer surface. Greatest improvement can be had if the particle removal is introduced at the earliest stages of the process such as prior to diffusions.

2. Design Objectives

The major goal of this project was to increase the reliability of the Megasonic cleaning operation in addition to improve the overall cleaning efficiency to a world class level. In the pursuit of these goals there were several other benefits. The biggest of course was the cost avoidances that were realized just on the materials used on the bench but the other benefit was the ability to have a fast turn around on the transducer design changes due to the proximity of the transducer manufacturer and the willingness of the manufacturer to be involved in a new approach to Megasonic cleaning. It should be noted that the transducer manufacturer, Blatek, is also the manufacturer of transducers for Submicron Systems, Reynoldstech, and others.

3. Description

a. Benchmarking

It was necessary to find out what kind of energy was being put into the baths to know a common reference point. To that end a Branson model 200 Cavitation Intensity meter was used for an arbitrary standard for the initial measurement. Although the Megasonic action does not actually cause cavitation in the fluid, this meter was able to give a means of measuring the molecular activity in the test media. The test transducers were both operating near 750KHz at an initial power of 250 watts CW. In figure 1 is the results of the data collected from the Verreq transducer that was used in the original Megasonic tank. The energy distribution is relatively high but not very uniform. In figure 2 the data from the first of the transducers from Blatek is shown. Energy on the average is slightly lower but is considerably more uniform. As an added note the match to the amplifier with the Verreq transducer was approximately 1.75:1 while the Blatek unit had a 1.02:1 ratio. The next stage of the experiment was to come up with a means of making the Blatek transducer have the same overall energy level as the Verreq unit while still maintaining the better uniformity in energy distribution.

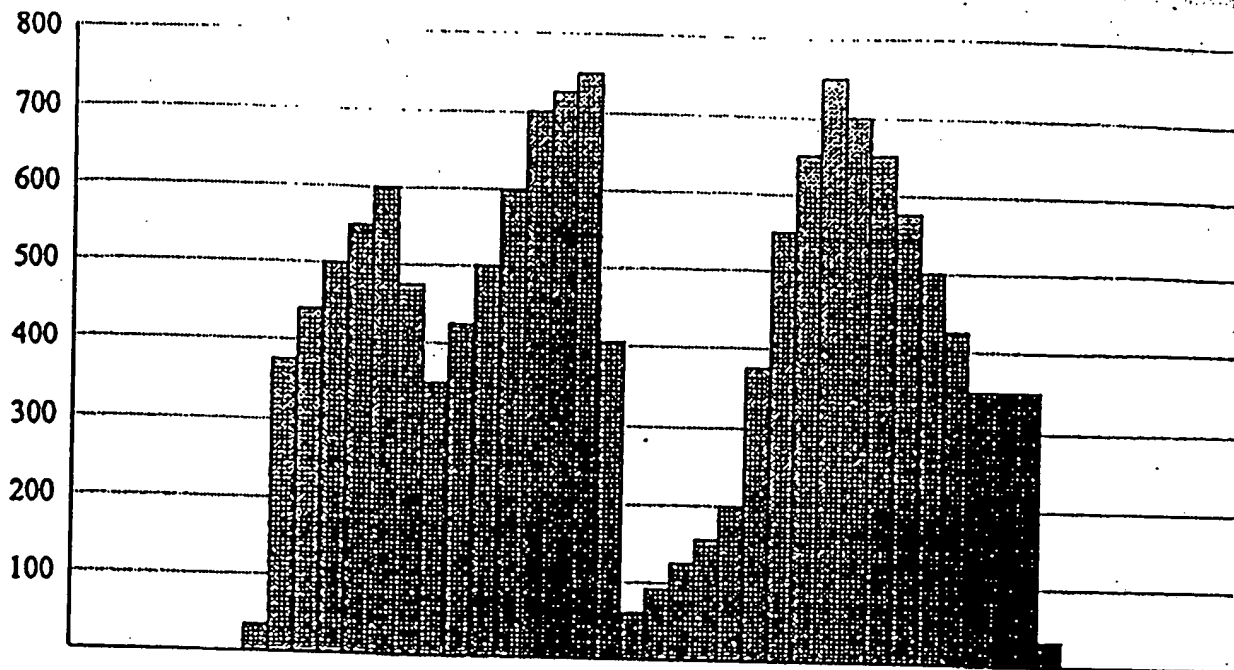


Figure 1 Cavitation Intensity (Cavins)
Verteq Transducer 750KHz 250 Watts CW

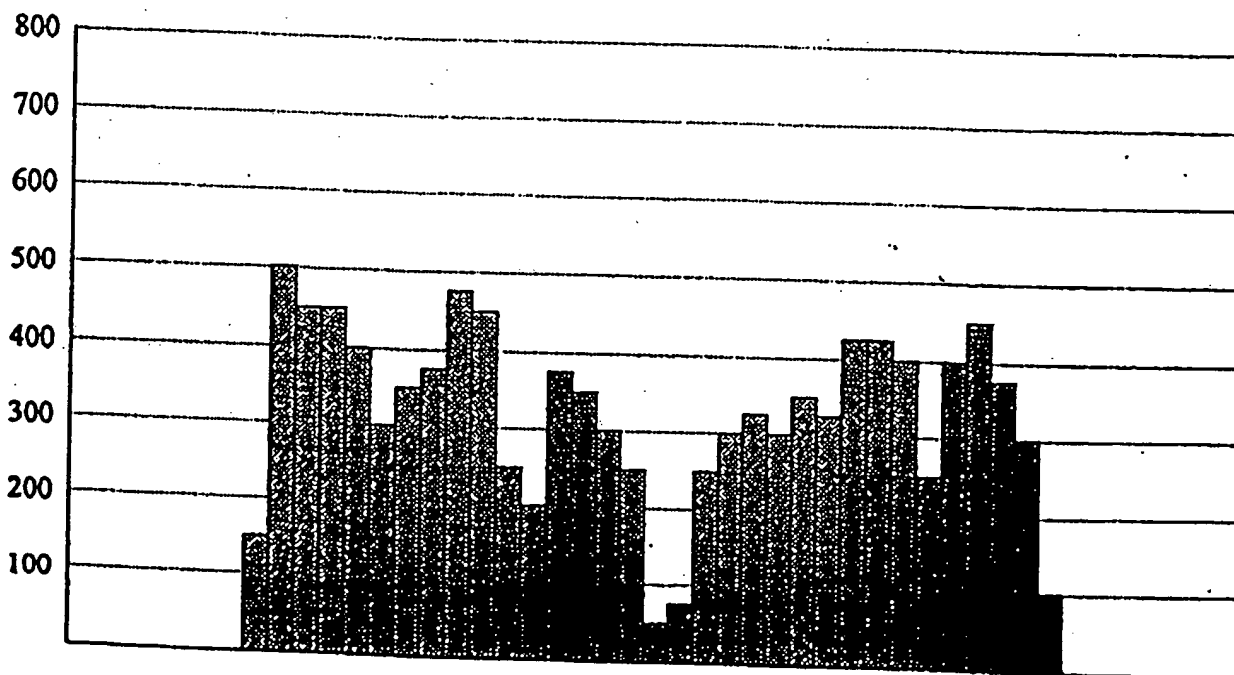


Figure 2 Cavitation Intensity (Cavins)
Blatek Transducer 759 KHz 250 Watts CW



b. Project Development

Once the benchmarks were established the level of energy in the Blatek transducer had to be brought up to at least the same amplitude as the Veriteq unit. On observation of the surface activity the Veriteq unit had a very sporadic rupture of the surface tension while the Blatek unit had a very uniform rolling of the surface above the transducer. Again indicating that the Blatek unit had a more uniform distribution of energy. The breaking of the surface tension is not exactly a desirable characteristic since the chemistry used in these baths contain hydrogen peroxide which will break down extremely rapidly under the conditions of lost surface tension, vaporizing. Excessive power, which also causes vaporizing, does not aid in particle removal efficiency.⁽³⁾

Consideration was then given to pulsing the RF energy at a 50% duty cycle to allow for a higher energy level without exceeding the average power on the transducer. To make the pulse rate synchronous with the fundamental frequency, the fundamental was divided by 2^{14} using a 14 stage ripple carry binary counter/divider. In figure 3 the cavitation energy can be observed up to and exceeding the level of the original Veriteq unit. The average level of the Veriteq unit in figure 1 is 433 Cavins while the average of the Blatek unit in figure 3 is 504 Cavins. In addition to the increased level of energy the pulsing of the RF has a similar effect as bead blasting in a pneudraulic system. With each molecule having an acceleration in the order of 100 kilograms being pulsed on and off at a rate of the fundamental divided by 2^{14} , cleaning is very effective.⁽²⁾

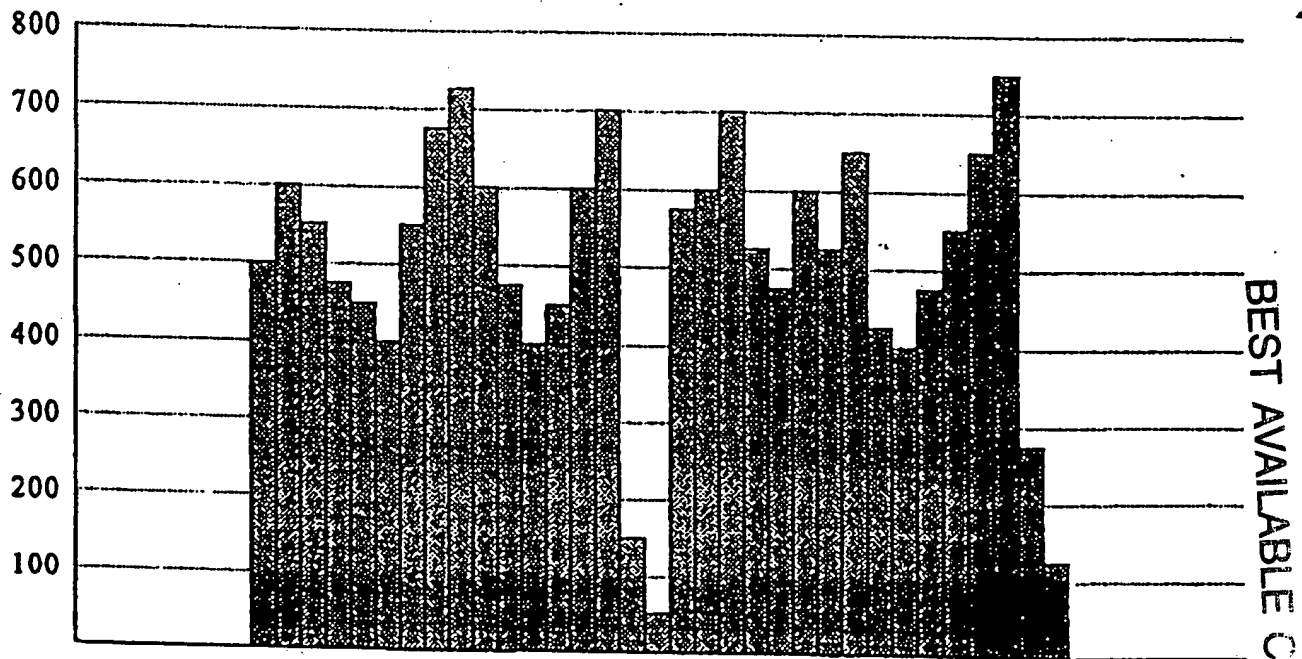


Figure 3 Cavitation Intensity (Cavins)
Blatek Transducer 759 KHz 250 Watts 50% Duty Cycle

i. The SC1 Tank

The physics of the SC1 tank then had to be resolved. The original design from the first bench of Mayer and Schwartzman used a tank that transitioned from left to right, had a sizable footprint, loaded on one end and unloaded at the other end. With the trend moving toward robotic control of such systems it was necessary to come up with a tank that could be loaded and unloaded from the same point. A new tank was designed integrating these factors (figure 4). In the Cavitation measurements of the transducers it can be noted that each has its own signature of slight peaks and valleys of energy concentration. To help negate and neutralize some of these effects a pair of transducers are placed side by side in an array. Moving the carrier over the transducers in a front to back motion gives twice the Megasonic action of the original tank with just one insertion. Once the particles are dislodged and put in suspension, it becomes apparent that if they are not removed from the bath they could become redeposited onto the wafer surfaces when the Megasonic energy is turned off. To reduce this effect a filtered recirculation system was added. The electronics to control the motion of the carrier employs a pulsed DC gearmotor and fiber optical sensing of the transition extremes. The process is begun at the press of a push button switch overhead and the speed of the tank is set to match the rest of the bench operations, typically 8 minutes per cycle.

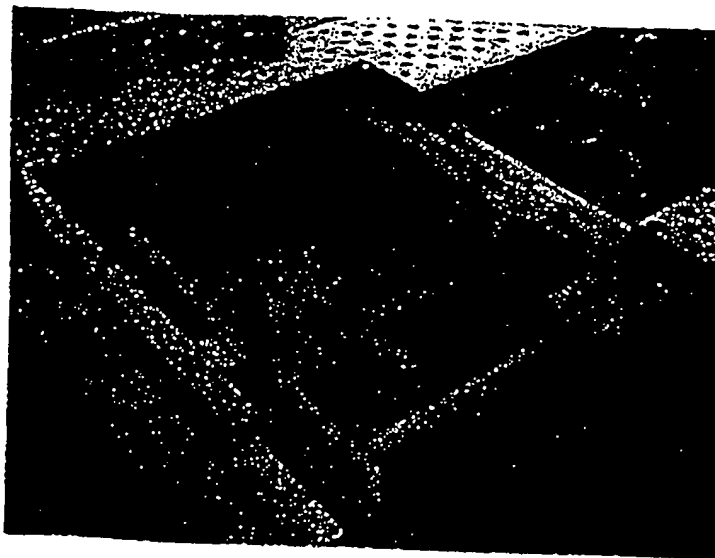


Figure 4
Newly designed SC1 tank

ii. The Transducer

The next issue to address was the physics of the transducer itself. The original transducer from Verateq used a tantalum face and a single wire from the end of each of

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the two crystals in the assembly. The first issue to address was the removal of the metal in the bath by replacing it with either PVDF (Kynar®) or 5/4λ quartz. The second issue is the current density on the crystal conductors when only a single wire connects to the excitation. To eliminate this situation bus bars are used behind each of the crystals to distribute the current evenly. Shown in figure 5 is a typical crystal for the SC1 tank using a G10 glass-epoxy frame. Other frame materials have been used and of them the better choice is natural polypropylene since it is very easy to machine and has a minimal number of impurities imbedded. Kynar® is also being considered for the same reasons.

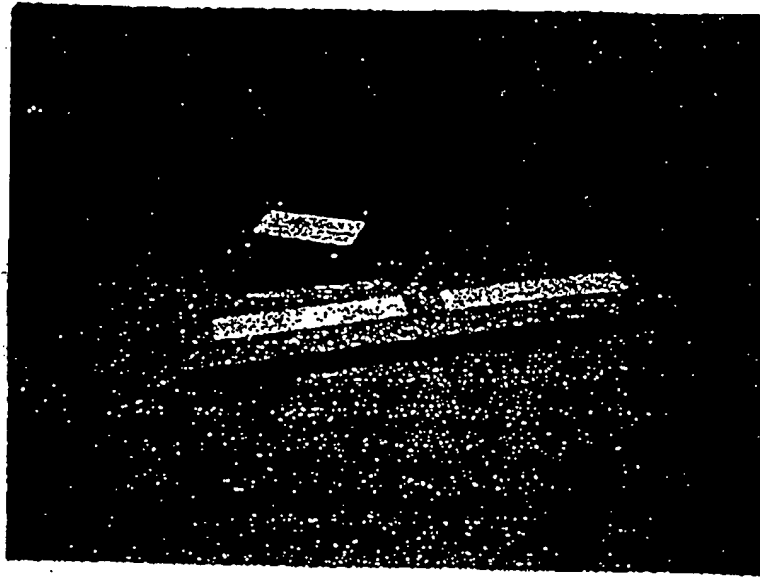


Figure 5
A typical SC1 transducer and matching network

iii. The Quick Dump Rinse Tank

When the bulk of the chemical cleaning is completed it is then necessary to rinse the residual chemicals from the wafers. In the past the conventional rinsing technique has been to use a series of overflow rinse tanks of hot and/or cold DI water. These are valid methods to remove residual chemicals but are not very aggressive and do nothing for the removal of any particulate contamination from either the previous baths or for any of the particles that may be introduced from the rinse bath itself. As an improvement to the overflow rinse a quick dump rinse is available off the shelf from Reynoldstech, Syracuse, New York. These tanks as shown in figure 6 are neatly compact and fit into the bench quite easily. With a controller from Modutech, San Jose, California, the quick dump rinse system can be programmed to match the rest of the bench operations. This controller uses electronics for the programming and pneudraulics for the external interface, eliminating the presence of metals in the bench.

The only remaining improvement to assist this very aggressive rinsing method would be to add a Megasonic transducer assembly.

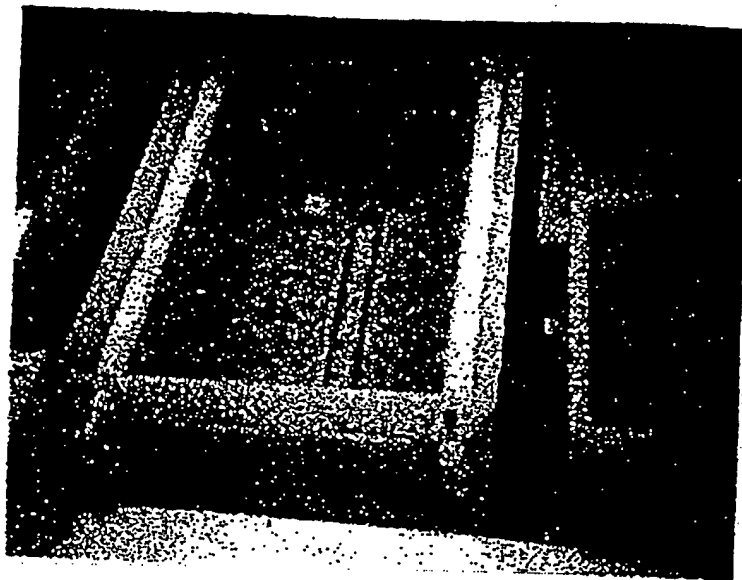


Figure 6
Quick dump rinse tank

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iv. The Quick Dump Rinse Transducer

Ideally the Megasonic energy should be energized at all times to keep any particles in suspension until they are rinsed into the overflow or are dumped. To perform these functions a transducer assembly had to be designed. The assembly that was finally designed is a "drop-in" module that requires no changes to the quick dump rinse tank. A float switch was incorporated in the base of the module to disable the RF energy when the water level is less than one inch over the transducer to provide the necessary cooling. Approximately 20 mm. above the flat transducer is a solid 17 mm. diameter quartz rod to distribute the energy evenly through the water by a series of interference patterns. (figure 7) Excitation is provided to the transducer using the same method as the SC1 tank with a 50 % duty cycle for maximum cleaning efficiency. Having the RF energy on at all times keeps any suspended particles from redepositing at the meniscus when removing the wafers from the tank.

v. The Phase Locked Loop Power Generator

To this point no effort has been put on the quality of the excitation to the transducers used in these newly designed tanks. In the original systems a stand alone function

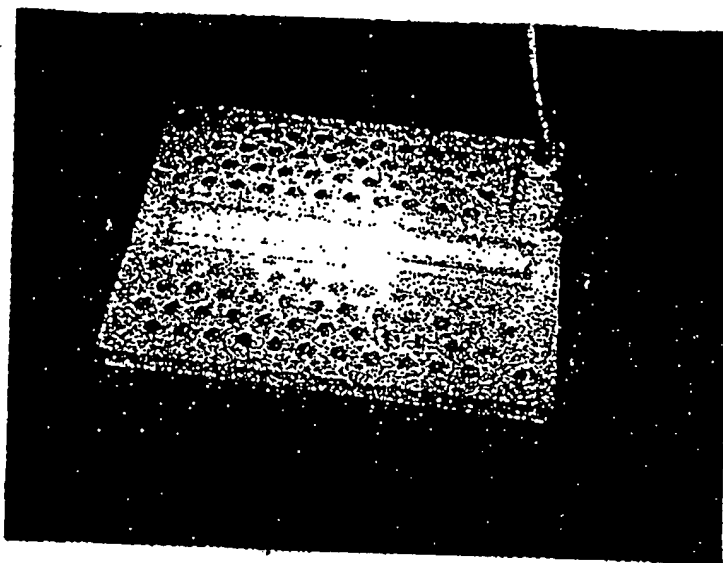


Figure 7
Drop in quick dump rinse transducer assembly

generator is used in conjunction with a stand alone class C power amplifier. Typically a Heath analog function generator was being employed as the frequency source. With the way the voltage controlled oscillators in these generators were designed, they had a tendency to drift with minor changes in environmental conditions. When the newer Blatek transducers were introduced into the cleaning operations with the impedance analysis provided by Blatek (figure 8) the method previously used to "find the resonance" of the transducer was not the correct method to get the maximum amount of transducer efficiency. To help facilitate using the designed frequency of the transducer, a B&K function generator with an internal frequency counter installed was used. The amplifier used to drive the transducer arrays was still the ENI model 1040L and of course this amplifier has a limited frequency range that rolls off starting at 500 KHz. The transducers used to this point have a resonance of around 750 KHz. To get the operation more efficient an amplifier with a higher frequency limit was needed and as a first choice the ENI model 400B was selected. This amplifier has a bandwidth of 80 KHz. to 2.7 MHz. with a 400 watt capability. It seemed to be the answer to the power/frequency problems. Unfortunately the operation of the new transducers requires that the excitation be pulsed at a 50% rate and even though the ENI 400B is rated for pulsed service, it failed profusely.

This situation was serious because there is very little equipment on the open market with the ability to perform at the frequency and power levels required for this service. To address this problem, a new approach was taken by designing a class D amplifier and since it is class D, digital drive is ideal. The perfect answer to the needed driver

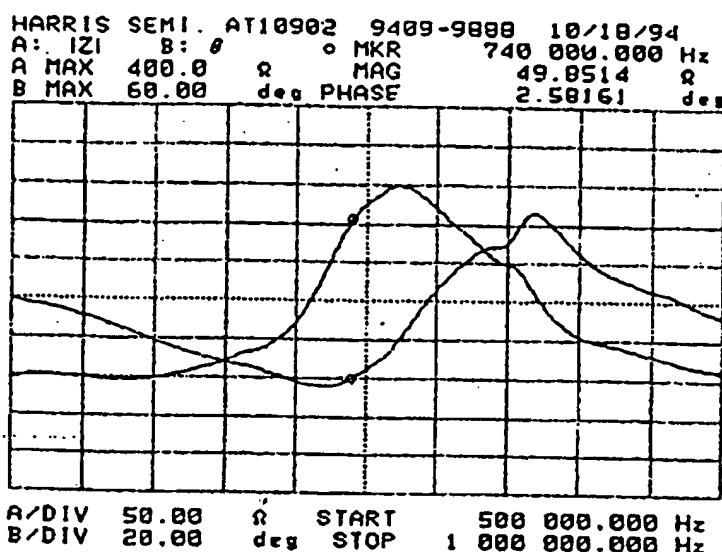


Figure 8
 Typical transducer impedance analysis

was a phase locked loop generator. In figure 9 the circuit shown uses a 4.096 MHz crystal with a $\pm .005\%$ accuracy as its reference. This reference is then fed into the phase locked loop circuit to select the desired operating frequency needed for the transducer being used. From the PLL circuit the signal is then gated by an external switch closure to enable the output of the generator. The externally gated PLL signal is then gated internally one more time through a 14 stage binary divider before going into the driver section. From the driver section the signal is then coupled into the quad switch array which functions as the output stage. With this configuration of output circuit, powers up to 1 KW are available. The output signal is sampled by a window comparator to indicate that the RF energy is active within an operational window or being told to be disabled with a green LED indicator.

There were immediate benefits to the new design of this power generator. Physically the new generator occupies only 30% of the volume of the 1040L (850 cubic inches vs. 2880 cubic inches) and weighs about half the weight of a 1040L (32.5 pounds vs. 60 pounds), both of these parameters do not take into account the external function generators needed when using the 1040L. Two really big gains since it is extremely advantageous to mount these units above the wet bench to preclude damage caused by accidental chemical spills. Electrical efficiencies in excess of 85% are achieved with the class D generator compared with a 30% efficiency of the class C 1040L amplifier. Power consumption of about 900 watts for an output of 750 watts of RF energy are typical compared to 1500 watts for an output of around 250 watts. This reduced power efficiency is caused by operation above the 500 KHz limit of the 1040L.

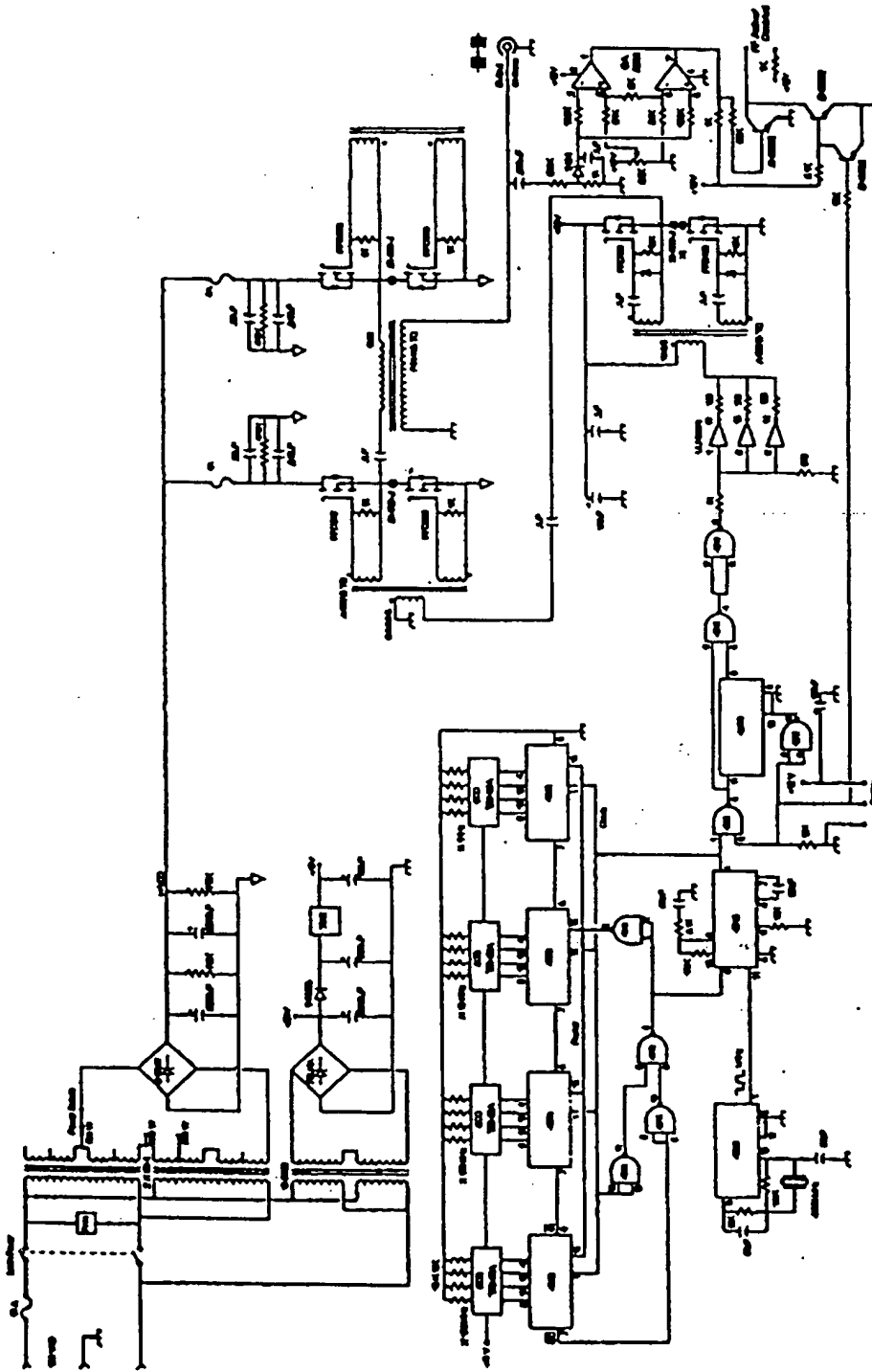


Figure 9
Schematic diagram of the phase locked loop power generator

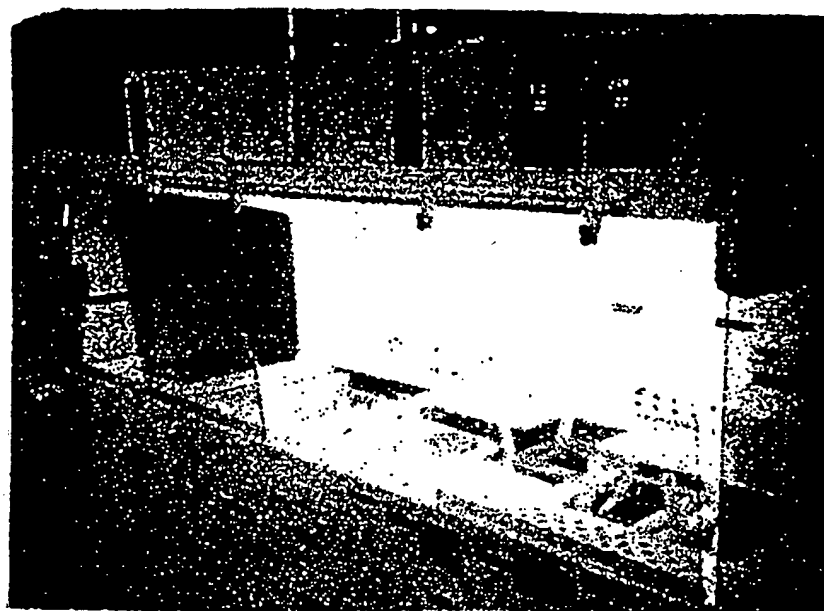


Figure 10
The complete clean bench

B. SYSTEM PERFORMANCE

1. Benchmarking

To run a performance test of a megasonic system there must be a suitable source of reasonably "dirty" silicon wafers. The standard technique for generating these wafers involves immersion in a 25% hydrofluoric acid deglaze bath. Typical results of this bath are wafers with 2000 to 3000 .3 μ m particles per six inch wafer. Normally a Megasonic system is able to remove 99% of the .3 μ m particles and tests run using a Tencor 7600 Surfscan to evaluate the cleaning effectiveness verified these results. A complete wet bench incorporating all of the Megasonic improvements is shown in figure 10.

2. Cleaning Efficiency

Figure 11 shows how the particle cleaning efficiencies improved as the wet benches in the oxide photo strip and Z Megasonic clean operations were modified. On the graph in the fourth month of FY '92 a single strip Megasonic transducer was introduced into the Z Megasonic clean sink. In the ninth month of FY '92 a double transducer strip was introduced into the same sink and the particle levels continued to decline to an almost immeasurable level by the beginning of FY '93. At the beginning of FY '93 the Oxide Etch Photo Strip sink had a Megasonic tanks installed and particle levels in both operations were extremely low. Not shown is the .15 μ m data which reached an efficiency of 97% after the bench modifications were completed.

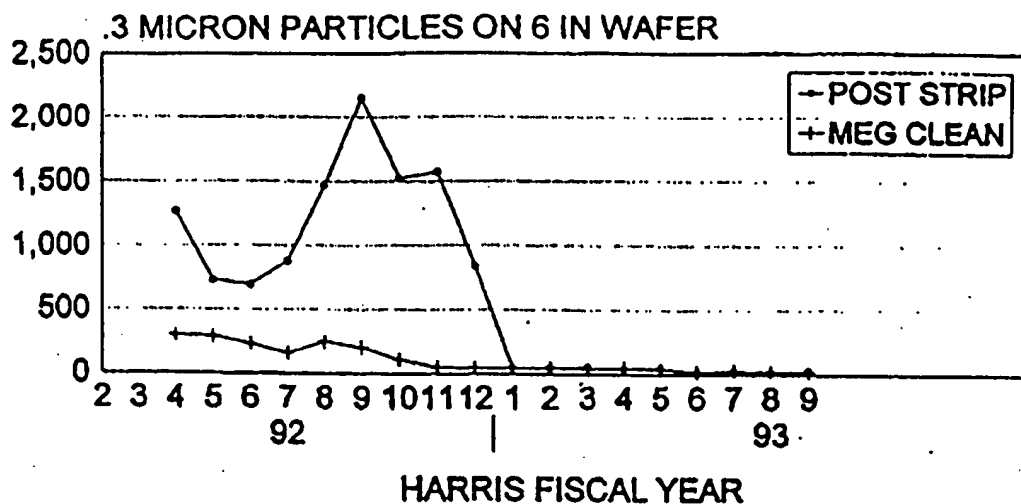


Figure 11
Particle removal improvement from Megasonics

3. Yield Effects

As each improvement was made with the wet bench cleaning systems in the fab there was a corresponding improvement in the average probe yield. In figure 12 each change in the bench cleaning component shows its reflected yield improvement. The introduction of the single strip Megasonic transducer in the fourth month of FY '92 caused the yield to climb from the 50% level to nearly 70% very rapidly. With the introduction of the second transducer in the ninth month the level climbed again to almost 80% and finally with the introduction of the Oxide etch photo strip Megasonics in the beginning of FY '93 the yields stabilized at a little over the 80% level.

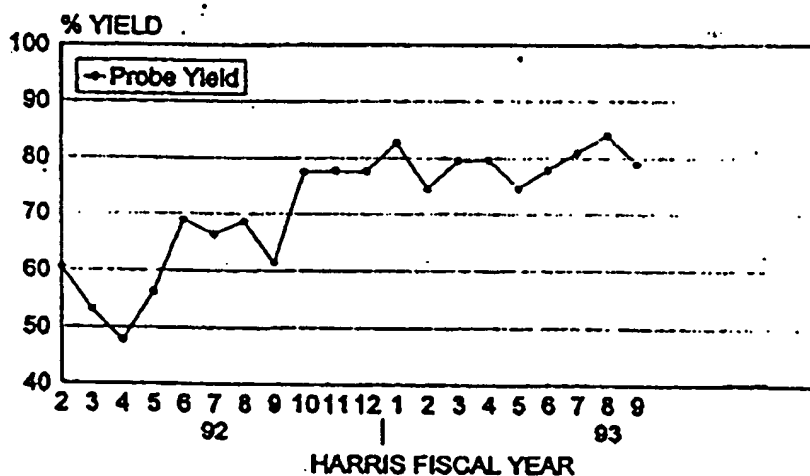


Figure 12
Probe yield improvements from Megasonics

C. Conclusions

The previously existing Megasonic cleaning systems were examined and their deficiencies were noted. After benchmarking the overall cleaning ability of these systems using standard "dirty" wafers, equipment improvements to make it compatible with the trends in modern semiconductor processors were initiated. First the original tantalum faced transducer was redesigned with a nonmetallic face at a considerably lower price, a better efficiency due to a precise impedance match and at a better reliability. Operation of the transducers at a 50% duty cycle provided an enhanced cleaning with no increase in average RF energy.

Tanks used in the SC1 and the quick dump rinse operations were then redesigned to be more compatible with the industrial trends. The footprint of the SC1 tank was reduced to half its previous size and was able to be loaded and unloaded from a common point affording compatibility with robotic systems. Quick dump rinse tanks were introduced to benches that had overflow rinse tanks and a drop in Megasonic transducer array was developed to integrate particle removal into the rinse operation.

The generation of the RF excitation for the Megasonic transducers had to be made more reliable and to that end a new digital power generator was designed and fabricated. The new generators operated more efficiently and was cheaper to manufacture than the previous equipment.

Particle removal of better than 98% at .3 um. from semiconductor wafers is easily attainable with the use of Megasonic cleaning systems of this generation. Cleaning efficiency of 97% at .15 um. was also attained. Probe yields have increase from the 50% range to better than 85% by FY '95 with each improvement reflecting a corresponding gain.

The specific achievements made in this program have enhanced the ability to clean silicon wafers used in the manufacturing of semiconductors to a world class level. Most of these improvements are not yet commercially available but are under patent application and when completed could be licensed for manufacturing.

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